INTERNAL WORKING DOCUMENT NO. 86:19

ANALYSIS OF PLANTATION DEVELOPMENT USING LARGE SCALE COLOUR INFRARED PHOTOGRAPHY

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Department of Natural Resources and Energy
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December 1985

Summary

Large scale colour infrared photographs of two plantations. P-22-79 (3 years old at the time of photography) and TP-23-77 (5 years old at the time of photography) were obtained using a fixed wing aircraft (Cessna 172). The task was to determine if sampling from such photography would result in estimates for density, stocking, and tree height similar to ground estimates for these parameters.

In P-22-79 the same sample areas were located on both the ground and the photographs. This yielded favourable results concerning species identification and tree height determination. Optical estimation was the most acceptable method of determining tree height. Other methods considered were the parallax bar, shadow length and relief displacement.

Independent samples were taken, one from the photography and one from the ground, to estimate parameters for the entire plantation. A comparison of these results suggested that it was possible to use this photography to determine stocking, density and tree heights for a plantation. However, after a trial sampling, in an area where the interpreter had no prior knowledge, TP-23-77, it became obvious that the favourable results for P-22-79 were strongly biased by the sampler's prior knowledge of the plantation. For the test plantation (TP-23-77) the only information which can be interpreted from this photography is an estimate of the number of planted trees. No estimates for hard-

woods were possible. Sampling from this photography is not as cost effective as the presently employed ground sampling method if information other than density is required.

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INTRODUCTION

The cost of monitoring plantation development (stocking, density, and height) increases every year. So much so, that other potentially more cost effective methods, such as large scale colour infrared photography are presently being investigated. The use of this photography could greatly reduce the amount of ground sampling required in plantations. Only in plantations found to be borderline in stocking, density, or average height (all of which should be determined from the photographs) would ground sampling be employed.

Large scale infrared photography has the following advantages for monitoring plantation development:

1) the sampling may be completed at the office anytime of the year.

2) results may be checked by other agencies and interpreters since the photograph produces a permanent record,

3) various sampling intensities may be used,

4) and inaccessible areas may be sampled (Hall, 1984).

In infrared photography, chlorophyll determines the reflectance colour of an object on the infrared film (Goba, 1982). The strongest contrast on a photograph may be obtained twice a year, in the spring just before "bud-burst" of hardwoods, or in the fall after the hardwoods have lost their leaves (Oliver, 1984). In either case the softwoods will appear bright red because they contain chlorophyll in their needles, whereas background material, such as soil, grass and slash, do not (Goba, 1982).

Although this method easily distinguishes between hardwoods and softwoods, there is still the difficult task of distinguishing between planted trees and natural softwood regeneration. Since spruce and fir have a similar reflectance colour and spruce is considered acceptable regeneration and fir is not it is critical to separate the two (Forest Management Manual for Crown Lands, 1984).

A second major problem is the accuracy of height estimates for planted trees. The scale of the photograph and the skill of the interpreter will have the strongest affect on the height determination for plantations.

The objective of this study is to determine whether large scale colour infrared photography (1:3600 contact print and an enlargement of 4.24 times) obtained in the manner described below, can be used to assess plantations. The plantations will be assessed in a similar manner as set out in the Forest Management Manual for Crown Lands. The density, stocking and height estimates for softwood trees only will be considered (Appendix I).

Study Location and Equipment

A Cessna 172 with a Hasselblad 500 EL camera (using a 70-exposure magazine) and either a 50mm or 150mm focal length lens was used to obtain colour infrared photography of 3 plantations at scales of 1:10,000 and 1:3600 (Oliver, 1984). A Delf Mirror stereoscope (4x magnification) and a Wild stereoscope (7.5x magnification) were used to interpret the photography.

Two plantations were used in this investigation:

P-22-79, jack and red pine 36 ha; plantation was 3 years old at time of photography (photographed Dec. 8, 1982).

TP-23-77, jack pine, 127 ha; plantation was 5 years old at time of photography (photographed Apr. 13, 1983)

Both plantations are located approximately 60 km northwest of Fredericton near Nashwaak Lake. The third plantation (TP-58-79) was rejected from the study because the spruce trees had not achieved a height greater than .75 m, and the photography was taken when there was snow on the ground.

Scale

The scale was calculated for each of the three study areas by dividing the focal length by the flying height above the ground. The photographs were ground truthed revealing scales larger than the desired 1:3600 and 1:10000. If several ground check points occurred on the same photographic frame, they were averaged. The average scale for each flight line was determined by averaging the averaged scale per photo frame. Thus the average scale for each flight line is as shown in Table 1.

Table 1. Target and ground truthed scale of photography flown by Oliver (1984).

Scale	P-22-79 (contact prints)	P-22-79 (enlarged prints)	P-22-79 (contact prints)	TP-58-79 (contact prints)	
Desired	1:3600	1:849	1:10000	1:3600	1:10000
Maps	1:3607	-	1:9967	1:3590	1:9979
Range	3067 - 3550	726 - 792	9300 - 10648	2955 - 3521	7745 - 8980
Avg.	1:3305	1:770	1:9949	1:3118	1:7951

Scale	TP-23-77 (contact prints)	TP-23-77 (contact prints)	TP-23-77 (contact prints)	TP-23-77 (enlarged prints)
Desired	1:3600[a]	1:3600[b]	1:10000	1:849
Maps	1:3365	1:3365	1:10010	-
Range	2445- 3253	2616 - 3400	8533 - 9235	590 - 665
Avg.	1:2762	1:3112	1:8751	1:635

a,b - represents two different flight lines flown at the same scale. Further explanation about scale is presented in Appendix II.

The 1:3600 photographs were taken using a 150 mm focal length, except in TP-23-77 where 2 passes were made using a 50 mm focal length. All other photography was taken using a 50 mm focal length.

Since the contact prints were only 5.5 cm^2 at a scale of 1:3600, scale checks on the ground were quite difficult. However, after enlarging these photographs 4.24 times it was much easier to locate acceptable ground control points. The percent error in scale can be reduced from 14.6% to 8.6% by using enlarged photographs. This is explained in two ways:

1. Better ground control points may be depicted on the enlarged photographs
2. A half a millimeter error in measurement on the 1:3600 photos represents 1.8 m on the ground whereas the same error on the 1:849 scale represents only .4245 metres on the ground.

Development Plantation

Direct Comparison of Ground and Photography

P-22-79 was used to assess the photography and develop methods of height determination. The other plantation, TP-23-77, was reserved as an area the interpreter was not familiar with and used to assess the potential of the interpretation methods.

Sample areas were established within P-22-79. Tree species were identified, and heights were recorded. It was necessary to count back 3 years of growth to determine tree height, because the photography was 3 years old. Counting back years of growth may be a significant but an unavoidable source of error in the study. All softwood trees above 30 cm and all hardwood trees above one meter were tallied. Every tree was assigned a number, and a map/sketch was made of the sample areas depicting the relative location of one tree to another. These same sample areas were precisely located on the photographs. The interpreter mapped/sketched each of the sample areas numbering the trees/clumps. Each tree was identified and assigned to a particular height class. A comparison of the two sketches revealed any trees which were present on the ground but were not detected on the photograph. These errors of omission, by species and height, are presented in Appendix III. These errors occurred with jack pine and red pine less than one meter and with balsam fir less than six tenths of a meter. For trees which were not part of a clump, the

species identification was correct 93% of the time. However, misidentification still occurred with shorter trees; balsam fir and jack pine (0.7 m), and spruce and fir (0.6 m) (Appendix III).

The question of whether spruce can be distinguished from fir remains unanswered since single stems greater than 0.75 m in height of spruce and fir could not be located. The spruce which was present was either too short (0.75 m), obscured by shadow, or more commonly, intermixed with fir in a clump distribution. Three fir, growing so close together that they would have to be pulled apart to be counted when on the ground, appear as a spruce because of the denser number of needles reflecting a deeper shade of red. The interpreter had to make an educated guess as to the number of stems in each clump since the individual stems/leaders could not be seen.

An estimate of the number of hardwood stems in each plot was not possible, since hardwoods can only be detected at high densities. Pin cherry was more easily detected than aspen in the late fall photography. In order to estimate the number of hardwoods present, "leaf on" and "leaf off" photography should be compared. This comparison of "leaf on" and "leaf off" photography should facilitate the determination of"free-to-grow" trees.

Height

Four methods of height determination were investigated:

1. Parallax bar (Appendix IV)
2. Shadow length (Appendix IV)
3. Relief displacement (Appendix IV)
4. Optical estimation (Appendix III)

The parallax formula is quite sensitive to deviations in 'dp' (the measurement achieved with a floating dot). This method is very time consuming and results were only correct to within 0.5 m.

The shadow length method was difficult because shadows were obscured within the plantation. Also, any slope present would strongly alter the length of the shadow being measured.

The relief desplacement method did not give results consistent with ground measurements (Table 2).

Table 2. Tree height estimates for shadow length and relief displacement methods.

Tree #	Height Ground Measurement (m)	Height Shadow Method (m)	Height Relief Displacement Method (m)
1	.48	.47	.53
2	.50	.39	2.19
3	.42	.14	1.13
4	.32	.25	1.15
5	.22	.16	.60
6	.42	.28	.60
7	.84	.78	2.46
8	.46	.22	2.50

The fourth method is an optical estimate. In the first attempt using .5, .51-1.29, 1.3-2.0 height classes the interpreter was only able to place individual trees in the correct height class 67% of the time. A second attempt was made using the 1.29 and 1.3 m height classes. Trees were placed in the correct height class 83% of the time. However, it should be noted that few of the red pine in the 3 year old plantation had achieved a height of 1.3 m. Using these divisions for height class the interpreter's success was 74% with jack pine, 96% with red pine, and 100% with fir (Table 3).

Table 3. Percentage of trees placed in the correct height class by species using optical estimation (1.3 m class).

	1.29 m		1.3 m		
	Correct	Incorrect	Correct	Incorrect	Correct %
jP	31	13	12	2	74
rP	24	1	-	-	96
bF	8	0	1	0	100

A third attempt, using what appears to be a more natural height division within the plantations, .7 m and .71 m, and only the most 'open' trees in each sample area, revealed the following:

Table 4. Percentage of trees placed in the correct height class by species using optical estimation (0.7 m class).

	.7		.71		
	Correct	Incorrect	Correct	Incorrect	Correct %
jP	2	1	46	2	94
rP	3	0	24	2	93
bF	-	-	2	0	100
					* overall 94%

These percentages must be accepted with caution since the interpreter may be too familiar with sample area. Another source of error is having to count back three years growth on all species.

This early examination indicated that planted trees could be separated from other softwood regeneration and placed successfully within broad height classes.

Indirect Comparison of Ground and Photography Sampling

A comparison was made of ground sampling and photography sampling. On the ground 154 5 m^2 plots were established on a 20 m grid. On the photographs 220 plots were established on a grid corresponding approximately to 5 m^2 plots on a 20 m grid on the ground. The means, standard deviations and 95% confidence interval are presented in Table 5. "Acceptable regeneration", as set out in the Forest Management Manual for Crown Lands (1984), is pine and larch if greater than 1.3 m in height and all other softwoods except fir if greater than 0.75 m in height.

Table 5. Photo vs ground estimates in development plantation.

Division	Photograph*	Ground
Planted Trees Only	$\bar{x}$ = .45 trees/plot Sx = .8398 CI = .45 $\pm$ .12 Limits .33 -- .57 Stocking Est. = 30%	$\bar{x}$ = .45 trees/plot Sx = .7144 CI = .45 $\pm$ .13 Limits .32 -- .58 Stocking Est. = 34%
Planted Trees plus acceptable regeneration	$\bar{x}$ = .69 trees/plot Sx = 1.5064 CI = .69 $\pm$ .16 Limits .53 -- .85 Stocking Est. = 54%	$\bar{x}$ = .79 trees/plot Sx = 1.5465 CI = .79 $\pm$. 2 Limits .59 -- .99 Stocking Est. = 42%
All Softwoods 0.10 m	$\bar{x}$ = 3.1 trees/plot Sx = 5.0404 CI = 3.1 $\pm$ .30 Limits 2.8 -- 3.4 Stocking Est. = 61%	$\bar{x}$ = 3.71 trees/plot Sx = 5.8911 CI = 3.71 $\pm$ .39 Limits 3.32 -- 4.1 Stocking Est. = 65%

* These confidence intervals apply to the trees which appear on the photographs. It is assumed that the rest of the plantation does not differ significantly from the area photographed.

Confidence intervals overlap in all of the divisions (planted trees, planted trees plus acceptable regeneration, and all softwood .10 m). This indicates that the estimates from the photographs are at least as good as the ground sampling methods for this particular plantation. Photo and ground estimates of stocking, for each division were within 12% of one another.

The variation between the two sampling methods increases as clumping increases. The results in Table 5 might imply that the "acceptable regeneration" can be distinguished from the fir component of the plantation. However, this question of distinguishing between spruce and fir remains unanswered because of the small quantity of "acceptable regeneration" present in the plantation.

Test Plantation

TP-22-77, was used as the test area to compare photo and ground sample estimates. The bias of prior knowledge of the area was removed during this trial, because the interpreter was not familiar with the area.

The heights of planted trees, near the principal point on the photographs of TP-23-77 (scale 1:3600) were estimated using a shadow constant, parallax bar, and an optical estimate (Appendix V). The shadows could not be measured in many cases because they were undetectable or were obscured by another object such as a tree or stump. The heights calculated from detectable shadows were distorted (by slopes, etc). Because of the above-mentioned difficulties, no confidence interval was calculated for the shadow length method.

Although only fourteen trees were viewed the average parallax bar and optical height estimates did not differ greatly from average ground sampling estimates (Table 6). The average tree height of 1.47 m determined from ground sampling of (an average of tallest planted tree per plot of plots containing planted trees) falls within the confidence intervals for the parallax bar and optical height estimates.

Table 6. Average height comparisons for TP-23-77.

Parallax[1]	Optical[1]	Ground*
CI = 1.33 ± .44	CI = 1.44 ± .31	CI = 1.47 ± .14
.89 -- 1.77	1.13 -- 1.74	1.33 -- 1.61

Parallax[2]

CI = 1.49 ± .30
1.19 -- 1.79

* Average height calculated using the tallest planted tree in each sample plot with planted trees (h=87)

1 Average estimated planted tree height (n=14)

2 Average estimated planted tree height (n=28)

The ground sampling consisted of one hundred and six(106) $5m^2$ plots uniformly distributed throughout the plantation. Tree species and heights were recorded. The following height classes were used 30-50 cm, 50-75 cm, 75-135 cm, and 135+ cm. The height of the tallest tree for each species was also recorded. The stocking and average density of planted trees was 82% and 2280 trees/ha, respectively. The density of all softwood stems taller than 1.47 m was estimated at 3620 trees/ha. The mean, 95% confidence interval, and stocking estimates are presented in Table 7.

To make the sampling from the photographs more efficient a systematic sample consisting of a grid centered on every fourth photograph was used. On a 1:3600 photograph the grid represented thirty-six 20 m^2 plots spaced 20 m apart. The height classes used

were 0-0.749m; 0.75-1.29m and 1.3+. Trees were identified by species and placed in a height class using optical estimates. The height of the tallest tree for each species was also recorded. Several trees heights were measured using the parallax bar every time a sampling grid was used. The parallax method yielded an average height of 1.6m (Sx = .47 n = 19).

Two 1:3600 contact prints were randomly selected. These photos and the two photos on either side of the selected photos were enlarged. A grid consisting of thirty six $5m^2$ plots spaced 20 meters apart was used to sample from these enlarged photographs. The average tree height estimate from these photographs using the parallax bar was 1.16 m (Sx .42 n = 22).

The mean and 95% confidence interval for density estimates, and the stocking estimates, for both the ground and photograph (1:3600 and 1:635) surveys of the test plantation are presented in Table 7. For all three divisions, the density estimates for planted trees alone, are similar and confidence intervals overlap. One explanation of lower density estimates for planted trees determined from the photography may be that the smaller trees are not being detected. When the density estimate includes "acceptable regeneration" (Spruce 0.75 m and pine 1.3 m), the ground estimates increase slightly, but the photograph estimates remain the same since no spruce or natural pine of appropriate height was detected. In accordance with the aforementioned manual a plantation must not exceed 3000 trees/ha. Although the manual states

that all tree species greater than or equal to the average planted tree height are to be included in this calculation, only softwood trees have been considered in the test plantation. From the ground estimate one would conclude that this plantation has exceeded this limit, but from the photo estimate it is substantially less dense than this limit. It becomes obvious at this point that a significant number of acceptable trees are not being detected from this photography. This situation worsens when all softwood trees are considered (Table 7).

When comparing the photo and ground estimates, density results for planted trees are similar, but stocking results differ considerably. Stocking is more strongly affected by whether a planted tree is included in a plot than is density. If a sample plot only contained one short planted tree, it would be considered stocked in the ground survey, and unstocked in the photo survey since it is unlikely that it would be detected. However, this would not necessarily have a strong effect on the density calculations.

The ground stocking estimates are noticeably higher than either of the two photo stocking estimates (contact prints and enlargement). The stocking is consistently underestimated using the photo estimates when compared to the ground estimates (Table 7).

Table 7. Photographs versus ground measurements in test plantation (TP-22-77).

Division	Planted trees (Trees/ha)	Planted trees + spruce .75m + pine & larch 1.3m (trees/ha)	All Softwood Stems 1.35m (spruce, fir, and pine) (trees/ha)	All Softwood Stems
Ground	$\bar{x}$ = 2280 CI = 2280 $\pm$ 340 Limits 1940 - 2620 Stocking Est. 82%	$\bar{x}$ = 2540 CI = 2540 $\pm$ 360 Limits 2180 - 2900 Stocking Est. 83%	$\bar{x}$ = 3620 CI = 3620 $\pm$ 460 Limits 3160 - 4080 Stocking Est. 98%	$\bar{x}$ = 9820 CI = 9820 $\pm$ 1040 Limits 8780 -10860 Stocking Est. 94%
* Photograph contact print 1:3600	$\bar{x}$ = 2109 CI = 2109 $\pm$ 140 Limits 1969 - 2249 Stocking Est. 62%	Same because no other pine or spruce talleyed	$\bar{x}$ = 2700 CI = 2700 $\pm$ 310 Limits 2390 - 3010 Stocking Est. 64%	$\bar{x}$ = 3167 CI = 3167 $\pm$ 205 Limits 2960 - 3372 Stocking Est. 76%
* Photograph Enlarged print 1:635	$\bar{x}$ = 2112 CI = 2112 $\pm$ 360 Limits 1752 - 2472 Stocking Est. 65%	Same because no other pine or spruce talleyed	$\bar{x}$ = 2520 CI = 2520 $\pm$ 440 Limits 2080 - 2960 Stocking Est. 67%	$\bar{x}$ = 7280 CI = 7280 $\pm$ 780 Limits 6500 - 8060 Stocking Est. 79%

* The confidence intervals apply to trees which appear on the photographs. It is assumed that the rest of the plantation does not differ significantly from the area photographed.

The photographs of TP-23-77 (test area) differ a great deal from P-22-79 (development area) in the degree of colour contrast between planted trees and natural regeneration. The test area was flown in the spring of 1983 whereas the development area was flown in the fall of 1982. This difference may be attributed to the trees possessing different spectral reflectance at the two times of year; atmospheric conditions such as sun angle at the the time of photography, or simply the age difference of the trees. The planted jack pine was quite pink in the 1982 photography and much closer to red, (much closer to the colour of the fir) in the 1983 photography. From Table 7 the smaller planted trees, for an undetermined reason, are not being detected in the 1983 photography.

Cost

The cost presented in Table 8 assumes that it would require only one day to assess the plantation either from the aerial photography or on the ground.

The cost of obtain the photography yourself is reasonable if you "do-it-yourself". It becomes even more reasonable when one considers that at present two separate assessments are completed on each plantation, one by the licensee and one check cruise by the Dept. of Forest, Mines and Energy. With the photography the check cruise costs only increase by the salary of the interpreter whereas the ground estimate costs double. If, however, information concerning hardwoods was deemed necessary, the photography method cannot compete with ground sampling since two separate flights would be required, one in the spring or fall ("leaf-off period") and one during the summer ("leaf-on period").

Table 8. Cost comparison of ground sampling versus aerial photography sampling of plantations.

	Description	Cost/ Plantation	If 2 samples* of Softwood Required	Hardwood Estimates Required
Ground	- salaries (2 people) + equipment + supervision + expenses, etc.	240	480	240
Contractor Photography	- fly photography $450/plantation - develop at 1:3600 $14/plantation - interpretation $90/plantation	554	644	1108
Do it Yourself	- ignoring capital cost of camera, steroscope, etc. - processing of film, plane rental, salaries, and interpretation	244	334	448

* Assumes licensees sample plantations and government checks assessment.

Conclusions

The following may be concluded about large scale colour infrared photography obtained using a fixed winged aircraft (Cessna 172) flown over 5 year old or younger plantations.

Optical estimation is the most effective method of determining the height of trees. Other methods considered were shadow length, parallax bar, and relief displacement.

If the interpreter has any prior knowledge about the makeup of a plantation, the density, stocking and height estimates will probably be strongly biased.

There is quite a difference in the apparent quality of photography flown at different times of the year. The reasons for this are beyond this study.

More trees seem to be detectable in the fall photography (shorter planted trees show up).

The estimates for the test area, reveal that the only practical purpose of this type of photography is to estimate the density of planted trees. Much more is required when assessing a plantation according to the Forest Management Manual For Crown Lands, pages

61-66,(1984) and these other parameters cannot be measured from the photography.

To determine hardwood density or other characteristics of hardwoods within a plantation would require flying during the "leaf-on" period in addition to flying in the "leaf-off" period to assess softwoods.

The question of whether spruce can be distinguished from fir remains unanswered since the spruce component of both plantations considered was low.

When compared with ground sampling, this type of photography is not cost effective for the amount or type of information it can provide to determine if a five year old plantation meets the standards as outlined in the Forest Management Manual (1984). If the photography is used to determine only density of planted trees the cost is similar to ground assessment.

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Acknowledgement

The author would like to thank Mr. Eric Wang (New Brunswick Executive Forest Research Committee Inc.), Mr. Robert Speer (Dept. of Forest, Mines, and Energy), and Mr. Steve Oliver (Dept of Forest Resources, U.N.B.) for the direction they have provided during the course of this project.

Appendix I

Assessment criteria for five year old plantations
(Forest Management Manual for Crown Lands, 1984)

(a) A minimum of 1 500 planted trees/ha, or a minimum of 1 500 trees/ha of planted and natural conifer trees except balsam fir which meet the minimum height criteria in (d)

(b) A maximum of 3 000 trees/ha of all tree species. The total trees/ha includes all planted trees and all natural regeneration that is equal in height or higher than the planted trees

(c) At least 75% stocking, based on planted and acceptable natural regeneration as outlined in (a)

(d) An average height of at least 1.30 meters for pine and larch species and 0.75 meters for spruce.

Planted trees and acceptable natural regeneration cannot be overtopped by other tree species and must be "free-to-grow". A stand is "free-to-grow" when it is within the minimum and maximum density standards set out above and is not experiencing growth interference from competing vegetation. Plantations will not be considered "free to grow" if more than 25% of the area (based on percent stocking) has competing vegetation which is greater in height than the planted and acceptable natural regeneration.

Appendix II

Basic Photogrametry

The scale is the cornerstone to any measurement taken from aerial photographs. It is the ratio of a linear distance measured on the photography (d) to the same linear distance measured on the ground (D). Scale may also be calculated using the ratio of the focal length of the camera (f) to the flying height above the ground (H^1) (Wolf, 1974).

$$S = \frac{d}{D} = \frac{f}{H^1}$$

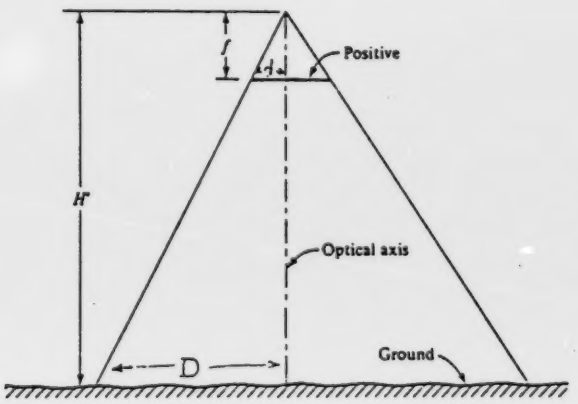


Figure 1. A vertical photograph taken over level terrain (Wolf, 1984).

Thus, a scale of 1:10000 means 1 cm on the photograph represents 10000 cm on the ground. Or, 1 cm in the photograph represents 100 m on the ground. Changes in either the focal length or the flying height of the aircraft above the ground can strongly affect the scale of the photograph. At a scale of 1:10000 1 cm^2 on the photograph represents 10000 m^2 or one hectare on the ground.

Example: 2 planes mounted with identical cameras fly at 500 m above the ground, one using a 150 mm lens the other a 50 mm lens.

$$S = \frac{f}{H} = \frac{150 \text{ mm}}{500 \text{ m}} = 1:333$$

Flying Height Above Ground (m)

	500	510	1000	1010	300	350
Plane A 150 mm lens	1:3333	1:3400	1:6667	1:6710	1:2000	1:2333
Plane B 50 mm lens	1:10000	1:10200	1:20000	1:20200	1:6000	1:7000

A change in flying height results in the following percent changes in scale:

10/500 = ± 2.00%

10/1000 = ± 1.00%

50/300 = ± 16.70%

10/300 = ± 3.33%

Thus the lower the aircraft flies the more strongly flying height deviations affect the scale of the photograph. Also, the longer the focal length the higher the aircraft can fly to achieve the desired scale on the photograph.

Desired Scale 1:3600 H^1 = 3600 X 150 mm H^1= 3600 X 50 mm

H^1 = 540 m H^1= 180 m

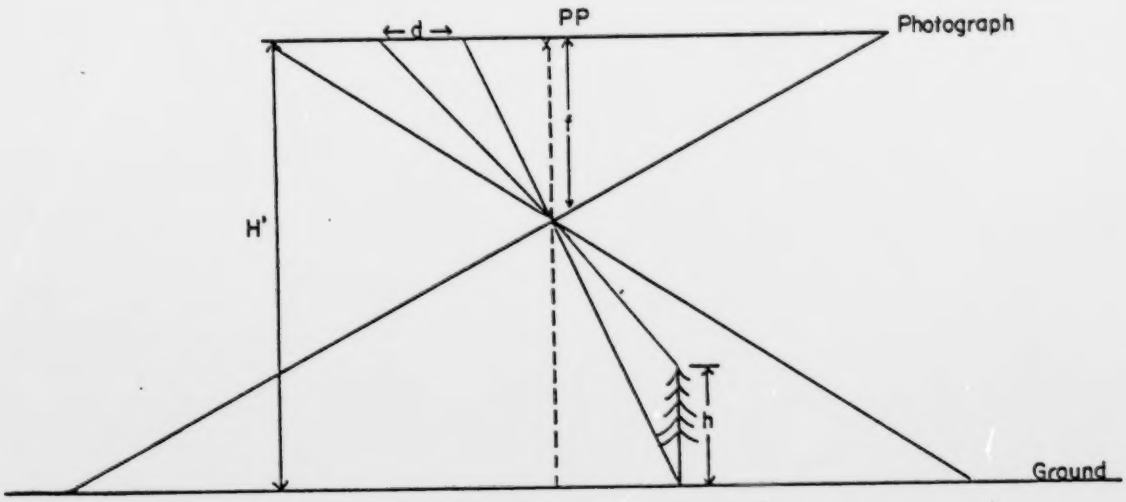
In the previously mentioned example a 10 m deviation in flying height caused the scale to change approximately 67 units when a 150 mm lens was used and approximately 200 units when a 50 mm lens was used. The longer focal length is desirable for the following reasons:

1. Scale of photographs is altered less when deviations in flying height occur.

2. The aircraft can fly at higher altitudes to obtain the desired scale.

3. The higher the aircraft flies the less relief displacement occurs.

Relief displacement is a result of variation in ground level.



pp - principal point on photo (geometric center of photo)

d - relief displacement

r - radial distance from the pp to the top of the object

h - height of object

H^1 - flying height

(Wolf, 1974)

$$d = \frac{rh}{H^1}$$

Because of relief displacement, high objects appear further away from the principal point and low areas (depressions in the

terrain) appear closer to the principal point, than is the case on the ground. It becomes obvious that the lower you fly the higher is the relief displacement on the photograph (Wolf, 1974).

Tilt is another factor which affects scale.

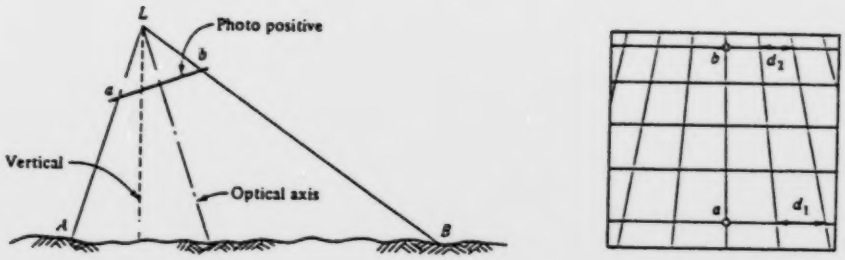


Figure 2. The effects of tilt on the scale of a photograph (Wolf, 1974).

Object A will appear at a different scale than Object B because of differences in distances from the photo positive (Wolf, 1974).

As a result of tilt d_2 appears shorter than d_1 when they are the same linear distance on the ground. The scale changes strongly across the photograph. Photographs are still considered 'vertical' if tilting is kept to less than 3°.

Changes in flying height and any tilting of the aircraft will always produce a negative affect on vertical photographs.

The relief displacement may or may not result in the same negative affect. If the terrain is relatively level the relief displacement formula may be used to determine the height of planted trees.

Appendix III

Table 1. Optic evaluation of sample area.

	Height Class m								
	Sp ID		0-.5		0.51-1.29		1.3+		
Sp	Corr	Incorr	Corr	Incorr	Corr	Incorr	Corr	Incorr	Omissions
jP	*						*		jP .52
bF	*				*				.38
bF	*						*		
jP	*				*				
rP	*				*				
rP	*				*				
rP	*				*				
rP	*					*(1.32)			
rP	*				*				
rP		*(bF)			*				rP .20
rP	*				*				.68
rP	*					*(0.4)			.54
bF	*				*				.44
bF	*				*				bF 1.08
bF	*				*				
bF	*				*				
S		*(bF)		*					
jP	*					*(2.14)			jP .22
jP	*					*(2.04)			.66
jP	*					*(2.06)			.82
jP	*					*(1.74	in	)	1.02
jP	*					*(2.20	shadow)		bF .26
jP	*					*(1.76)			.26
jP	*					*(1.84)			.20
jP	*				*				.46
bF		*(jP)				*(1.50)			.22
jP	*					*(1.36)			.22
jP	*						*		jP .84
bF	*				*				
jP	*						*		
jP	*						*		
jP	*					*(1.32)			bF .42
jP	*						*		.42
rP	*				*				.26
rP	*				*				.26
bF	*				*				rP .42
rP	*					*(1.48)			.44
rP	*				*				
rP	*				*				
rP	*					*(0.44)			56 bF not
rP	*				*				showing at
rP	*				*				height .6
rP	*				*				
rP	*				*				
rP	*				*				
rP	*				*				

Table 1. continued

	Height Class m								
	Sp ID		0-.5		0.51-1.29		1.3+		
Sp	Corr	Incorr	Corr	Incorr	Corr	Incorr	Corr	Incorr	Omissions
rP	*				*				
rP	*				*				jP .62
rP	*				*				
rP	*				*	*(0.46)			
rP	*				*				
rP	*				*				
S		*(bF)	*						
jP	*				*				
jP	*				*				
jP	*			*(1.04					
jP	*								
jP							*		
jP	*								
jP	*				*				
jP	*			*(.64)					
jP	*				*				
jP	*				*				
jP	*				*				
jP	*			*(.62)					
jP	*				*				
jP	*							*(1.2)	
jP	*						*		
jP	*						*		
jP	*						*		
jP	*					*(1.5)			
jP	*					*(1.4)			
jP	*					*(1.5)			
jP	*			*(.78)					
jP	*				*				
jP	*				*				
jP	*						*		
jP		*bFclump	*						
jP		*bFclump	*						
jP	*							* .5-1.3	
jP	*					*(1.38)			
jP	*				*				
jP	*					*(1.46)			
jP	*				*				
jP	*				*				
jP	*					*(1.42)			
jP	*				*				
jP	*				*				
jP	*				*				
jP	*				*				
jP	*				*				
jP	*				*				
jP	*				*				
jP	*				*				
jP	*				*				

Optic Estimate of Clump		Actual Components of Clump	
Species	Est. Height or Height Class	Species	Actual Height or Height Class
2bF	.5-1.329	1S 4bF	.5-1.29
2bF	.5-1.329	4bF	.44,.26,.22,.92
(15bF (4S	.5-1.329) .5-1.329)	(42bF (1rP	.5-1.29) .96)
6bF	.5-1.329	(10bF (1S	.5-1.29) 1.02)
10bF	.5-1.329	3bF	.5-1.29
2bF	.5-1.329	3bF	.5-1.29
2bF	.5-1.329	5bF	.46,.4,.5,.62,.60
4bF	1.3-2.0	10bF	1.29-2.0
8bF 1jP 1jP	.5-1.29)) .5-1.29) 1.3-2.0)	(29bF ((1S (jP	#20 .5-1.29 # 9 1.3+ .4 2.14
7bF 1S	.5-1.29) .5-1.29)	(5bF (2S (1jP	.5-1.29) .26,.80) .64)
bF 8jP 12bF	.5-1.29 .5-1.29) .5-1.29)	3bF (15bF (6jP (1S	.5-1.29 .5-1.29) .5-1.29) .5-1.29)
1bF	.5-1.29	7bF	5 .5-1.29 2 1.3+
jP	.5	2bF	.5,.86
3bF	.5-1.29	5bF	.5-1.29
1bF	.5-1.29	3bF	.5-1.29
1bF	.5-1.29	6bF	.5-1.29
2bF	.5-1.29	3bF	.5-1.29
bF	.5-1.29	5bF	.46,.26,.90,.58,.38
1jP 42bF		73bF 4jP 7S	

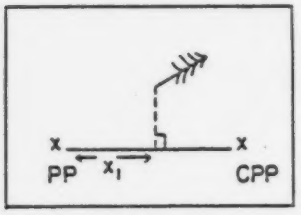
Optic Estimate of Clump		Actual Components of Clump	
Species	Est. Height or Height Class	Species	Actual Height or Height Class
bF	1.30-2.0	96bF	1.3-2.0
bF	.5	2bF	1.2
bF	1.3	2bF	1.58
bF	2.0-2.5	3bF	1.58
2bF	2.0-2.5	4bF	
1jP	.5-1.29	3jP	.86,.82,1.12
1jP	.5-1.29	5bF	.5-1.29
bF	.5-1.29	4bF	.5-1.29
1jP	.5-1.29	1S 11bF	.28 .28-1.08
2bF showed where 26 were present at a height of .54			
1bF		5bF 1S	.5-1.29 .5-1.29
1bF		1bF) 1jP)	.62-1.10
1bF		2jP 2bF	.46,.96 .86,.74
1bF		1jP 3bF	1.28 .68,.44,.30

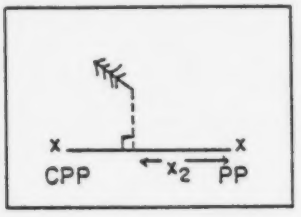
Appendix IV

Calculations for various methods of tree height determination

1. The parallax uses the formula $ho = \frac{Hdp}{P+dp}$ (Wolf, 1974).

where ho = height of object
H = height above base
dp = measurement from parallax bar (top to bottom of object mm)
P = absolute stereoscopic parallax (base)
(Wolf, 1974)





PP is principal point

CPP is conjugate principal point

$P = X_1-(X_2)$

$P = 5.40 -(-3.225)$cm

$= 8.625$ cm

14.615 mm measurement on parallax bar at the top of the tree

14.415 mm measurement on parallax bar at the bottom of the tree

$\therefore dp = 14.615 - 14.415 = .200$ H = 1775'

$$\therefore \quad ho = \frac{Hdp}{P+dp} = \frac{1775 \text{ ft.} \times 12 \text{ in./ft.} \times 25.4 \text{ mm/in.} \times .200 \text{ mm}}{86.25 \text{ mm} + .200 \text{ mm}}$$

$$= 1250 \text{ mm}$$

$$= 1.25 \text{ m}$$

if P = 8.725 cm then h = 1.24 m

if dp = .6 mm then h = 3.738 m

if dp = 1.2 mm then h = 7.42 m

if H = 1795 ft then h = 1.27 m

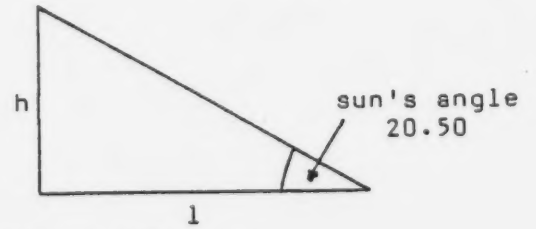
Thus the formula is most sensitive to deviation in dp. The use of the parallax bar is extremely time consuming and this interpreter could only estimate within .5m.

2. The second method tried was the use of shadow length. The sun's angle to the horizon was obtained from the University of New Brunswick. The following formula was used: $h = (l)(\tan O)$

where h = height of object

l = length of shadow measured on photograph

O = angle of the sum to the horizon at the time of photograph



if l = 100 m
h = tan 20.5 (100 m)
= 37.388

$$\text{scale} = \frac{f}{H} \quad \frac{1}{828} = \frac{150}{H}$$

$$\therefore \quad H = 150 \text{ mm} \times 828$$

$$= 124.2 \text{ m}$$

$\therefore$ shadow constant = $\frac{37.388}{100\text{ m} \times 10\,000\ (1/10\text{ mm/m})\ \ 828}$

eg. 1.5 mm (from photograph) = 15 10ths x .031 m = .47 m

3. For relief displacement $h = \frac{dH}{r}$ where h = height of object

d = length of object

r = radial distance from PP

H = flying height above ground

$h = \frac{.25\text{ mm} \times 124.2\text{ m}}{55\text{ mm}} = .53\text{ m}$

Appendix V.

Tree height estimates for test plantation TP-23-77.

I (mm)	Scale	Shadow Constant	Height (m)	Frame	dp (mm)	P (mm)	Height (m)	
0.5	1:2693	0.32	0.16	43	-	-	0.98)	
0.5	1:2892	0.35	0.17	44	0.43	25.00	2.84)	
0.25	1:3400	0.41	0.10	45	0.16	26.75	1.00)	
0.5	1:3086	0.37	0.19	46	0.265	24.80	1.70)	
0.65	1:3184	0.38	0.25	47	0.217	26.15	1.40)	
ns	1:3000	0	0	48	0.135	24.50	0.89)	
ns	1:2985	-	-	49	0.200	25.50	1.31)	
ns	1:3003	-	-	50	0.320	20.50	2.58)	CI=1.64±.45
ns	1:3100	-	-	51	0.37	34.00	1.81)	1.19 - 2.09
0.45	1:3038	0.37	0.16	52	0.212	23.85	1.50)	
0.25			0.09	53	0.16	24.00	1.11)	
0.25			0.09	54	0.27	25.75	1.75)	
0.18			0.07	55	0.27	26.25	1.71)	)
0.25			0.09	56	0.29	20.00	2.40)	)
								)CI=1.44±.30
	Optical Height (m)							)1.19 - 1.79
	1.4			20	.210	27.40	1.28)	)
	1.4				.15	26.60	.98)	
	1.3				.249	26.2	1.58)	
	1.0				.085	26.1	.55)	
CI=1.44±.31	1.5			22	.315	26.60	1.97)	CI=1.33±.44
1.13 - 1.74	1.0				.29	27.70	1.79)	.89 - 1.77
	2.0				.27	26.90	2.86)	
	1.4			24	.235	34.50	1.14)	
	1.4				.22	34.50	1.07)	
	1.4				.17	34.50	0.825)	
	1.4				.24	35.25	1.13)	
	2.0			26	.21	31.50	1.11)	
	1.5				.24	30.60	1.31)	
	1.5				.2	30.50	1.10)	